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Procedures for Preliminary Analysis of Tidal Inlet Hydraulics and Stability

by

Robert M. Sorensen

COASTAL ENGINEERING TECHNICAL AID NO. 77-8
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This report summarizes procedures for calculating the maximum tidal inlet channel velocity during a tidal cycle as well as the bay tidal range and phase lag (published by King, 1974). Guidance for the application of these procedures to solve tidal inlet design problems for jettied inlets is also presented. The procedures may be applied to some unjettied inlets. A procedure is described whereby the inlet hydraulic response calculations can be combined with the appropriate tidal prism-inlet area stability relationship
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from Jarrett (1976) to predict the probable stable inlet cross-sectional area, if stability is possible. An example is presented that demonstrates both the hydraulic response and channel stability calculations for a jettied tidal inlet.

PREFACE

This report describes simple procedures for calculating the hydraulic characteristics of a sea-inlet-bay system driven by the tide, as well as for estimating the expected stable channel cross-sectional area for a jettied entrance. It is based primarily on studies reported by King (1974) and Jarrett (1976) and it was written under the tidal inlets research program of the U.S. Army Coastal Engineering Research Center (CERC).

This report was prepared by Dr. Robert M. Sorensen, Chief, Coastal Structures Branch, under the general supervision of R.P. Savage, Chief, Research Division.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

John H. Cousins

JOHN H. COUSINS
Colonel, Corps of Engineers
Commander and Director

CONTENTS

TABLE

FIGURES

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.8532	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.1745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1]To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.
To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

SYMBOLS AND DEFINITIONS

A_b bay surface area

A_c channel cross-sectional area

A_{c*} channel cross-sectional area at each of n sections

a_b bay tidal amplitude

a_s sea tidal amplitude

B channel width

d average channel depth

d_b average bay depth

F friction term ($k_{en} + k_{ex} + fL/4R$)

f Darcy-Weisbach friction factor

g acceleration of gravity

K_1 friction coefficient

K_2 frequency coefficient

k_{en} entrance-loss coefficient

k_{ex} exit-loss coefficient

L channel length

L_b distance from inlet to farthest point in bay

L_* effective channel length

n Manning's resistance coefficient

P tidal prism

R channel hydraulic radius

R_* channel hydraulic radius at each of n sections

T tidal period

t time

V instantaneous average channel velocity

SYMBOLS AND DEFINITIONS--Continued

V_m maximum average channel velocity

V'_m dimensionless maximum average channel velocity

Δx channel section length

ε sea-bay tidal phase lag (degrees)

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PROCEDURES FOR PRELIMINARY ANALYSIS OF TIDAL INLET HYDRAULICS AND STABILITY

by
Robert M. Sorensen

I. INTRODUCTION

Preliminary design of proposed modifications (e.g., installation of jetties) at an existing tidal inlet or of a new inlet that is to connect an inland bay with the sea will require analysis of the hydraulic characteristics of the sea-inlet-bay system and determination of the probable stable dimensions of the inlet channel cross section. Although Section 5.73 of the Shore Protection Manual (SPM) (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1975)[1] discusses the various factors involved in inlet design, it does not provide guidance or specific techniques for conducting these analyses. This report presents methods for calculating the time-dependent average cross-sectional velocity in an inlet channel, the bay tidal level range, and the phase lag between sea and bay tides, as well as the expected stable channel cross-sectional area. Required input data for these calculations include the ocean tidal period and amplitude, the inlet channel length and hydraulic resistance, and the bay surface area. An example is presented to demonstrate these calculations for a hypothetical sea-inlet-bay system.

II. DEFINITION OF TERMS

Figure 1 shows an idealized sea-inlet-bay system. The jettied inlet channel has a length, L, width, B, average depth, d, cross-sectional area, A_c, below mean sea level (MSL), and instantaneous average velocity, V. Flow in the system is generated by a sea tide having a period, T, and amplitude, a_s, and results in a bay level response having the same period and an amplitude, a_b. The time of high water in the bay lags the sea high water by a phase lag, ε, usually given in degrees. A_b is the bay surface area and $2A_b a_b$, the volume of water that flows into and then out of the bay on a tidal cycle, is commonly known as the tidal prism, P. Parameters needed to define the inlet channel hydraulics include entrance- and exit-loss coefficients, k_{en} and k_{ex}, a resistance coefficient, f (Darcy-Weisbach) or n (Manning), and the hydraulic radius, R, which equals the cross-sectional area divided by the wetted perimeter. The acceleration of gravity is g.

III. TIDAL INLET HYDRAULICS

King (1974)[2] solved the basic equations of motion and continuity for an inlet-bay system (Fig. 1). He presented curves for the dimensionless

[1]U.S. ARMY, CORPS OF ENGINEERS, COASTAL ENGINEERING RESEARCH CENTER, *Shore Protection Manual*, 2d ed., Vols. I, II, and III, Stock No. 008-022-00077-1, U.S. Government Printing Office, Washington, D.C., 1975, 1,160 pp.

[2]KING, D.B., "The Dynamics of Inlets and Bays," Technical Report No. 22, Coastal and Oceanographic Engineering Laboratory, University of Florida, Gainesville, Fla., Mar. 1974.

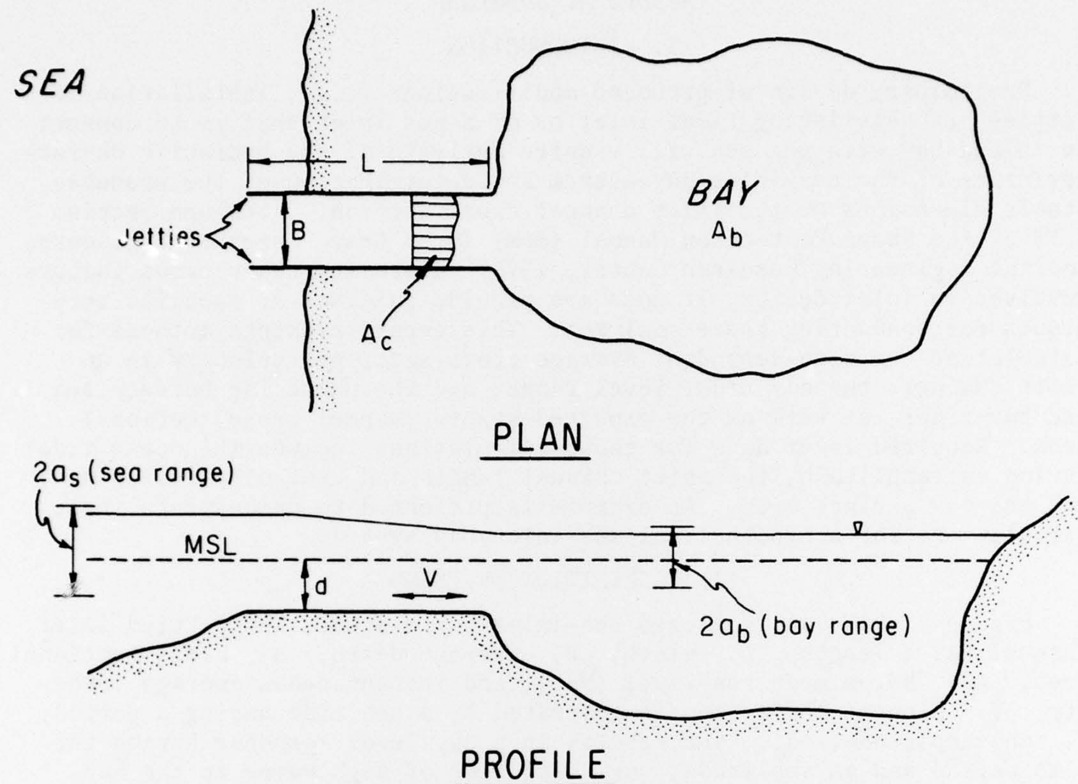

Figure 1. Sea-inlet-bay system.

maximum channel velocity during a tidal cycle, V_m', the ratio of bay to sea tidal amplitude, a_s/a_b, and the phase lag, ε, as a function of a friction coefficient, K_1, and a frequency coefficient, K_2 (Figs. 2, 3, and 4). He defines

$$V_m' = \frac{A_c T V_m}{2\pi a_s a_b}, \quad (1)$$

$$K_1 = \frac{a_s A_b F}{2 L A_c}, \quad (2)$$

and

$$K_2 = \frac{2\pi}{T} \sqrt{\frac{L A_b}{g A_c}}, \quad (3)$$

where V_m is the maximum velocity during a tidal cycle and

$$F = k_{en} + k_{ex} + \frac{fL}{4R}. \quad (4)$$

With values of a_s, T, k_{en}, k_{ex}, f, L, R, A_b, and A_c, K_1 and K_2 can be evaluated from equations (2) and (3); V_m', a_s/a_b, and ε determined from Figures 2, 3, and 4; and V_m calculated from equation (1). Note in Figure 3, for certain K_1 and K_2 values, $a_b/a_s > 1$ (i.e., bay range is amplified). This occurs when the inertia of the water in the channel exceeds the frictional resistance.

The major assumptions made in the development by King (1974)[2] are:

(a) The sea tide is sinusoidal; i.e., $\eta_s = a_s \sin 2\pi t/T$ where t denotes the time elapsed. Since the channel resistance is nonlinear, the channel velocity and bay tide will not be sinusoidal. However, for a first approximation $V \simeq V_m \sin 2\pi t/T$ and $\eta_b \simeq a_b \sin 2\pi t/T$ can be assumed. Thus, the average velocity over the flood or ebb phase of a tidal cycle is approximately equal to (2/3) V_m.

(b) The bay water level rises and falls uniformly (i.e., bay water surface remains horizontal). This assumption requires that the tidal period be long compared to the time required for a shallow-water wave to propagate from the inlet to the farthest point in the bay; i.e.,

$$t \gg \frac{L_b}{\sqrt{g d_b}} \quad (5)$$

[2]KING, op. cit., p. 9.

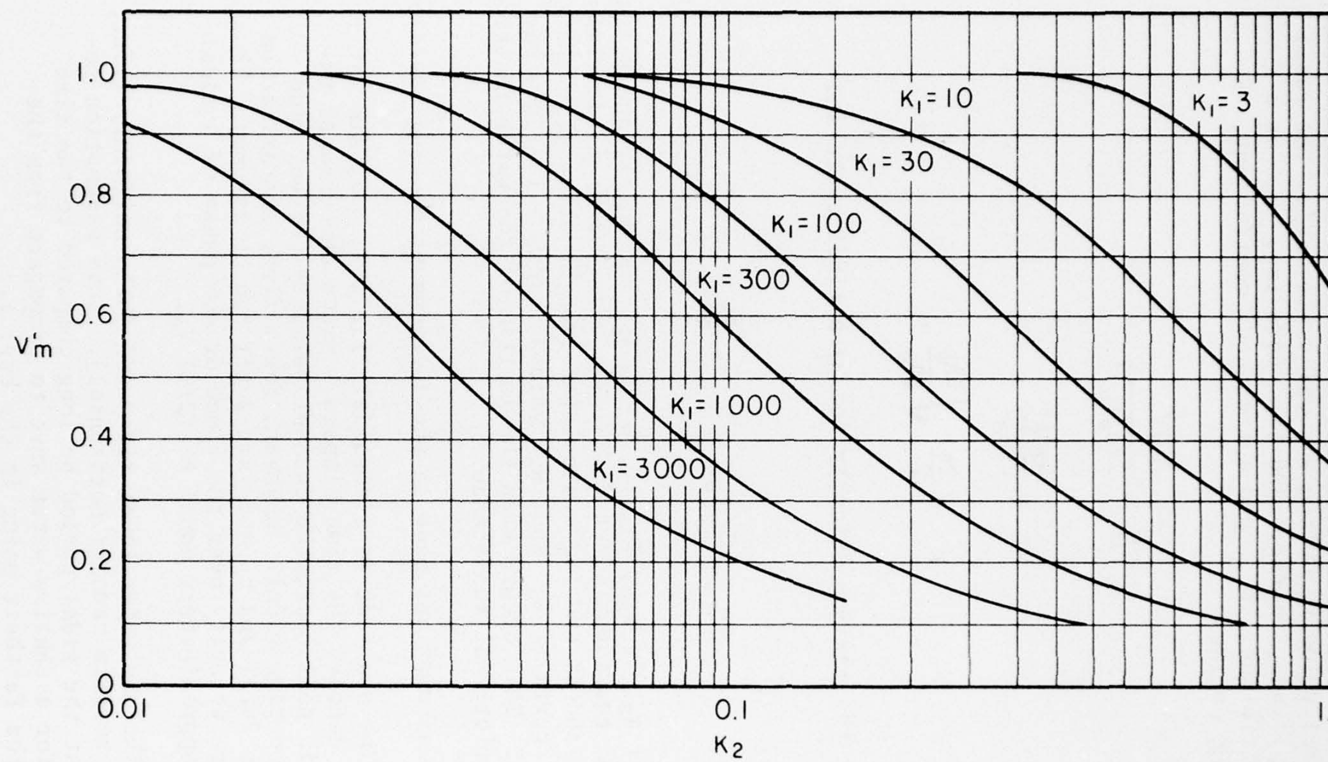

Figure 2. Dimensionless maximum velocity versus K_1 and K_2.

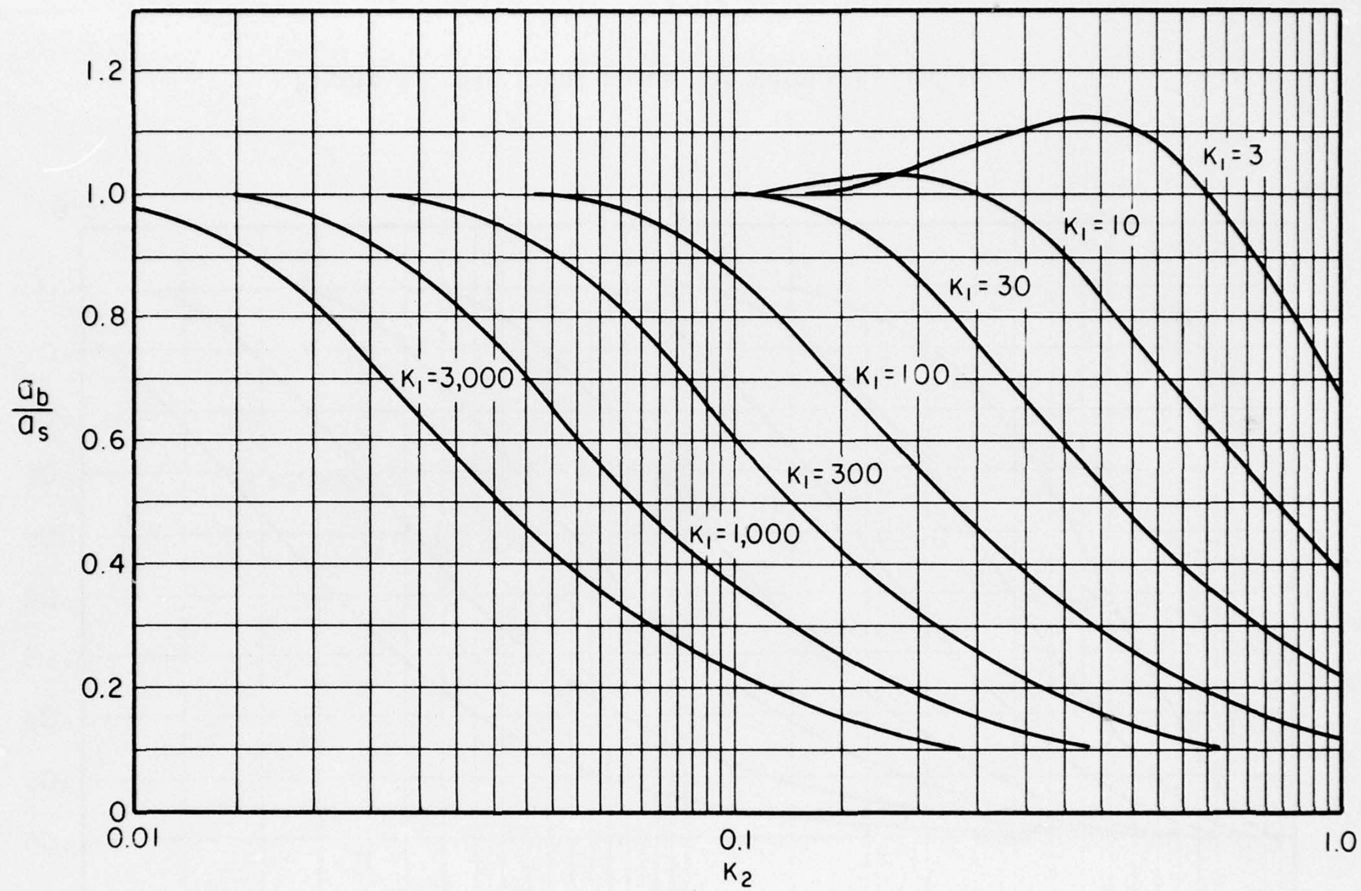

Figure 3. Ratio of bay to sea tidal amplitude versus K_1 and K_2.

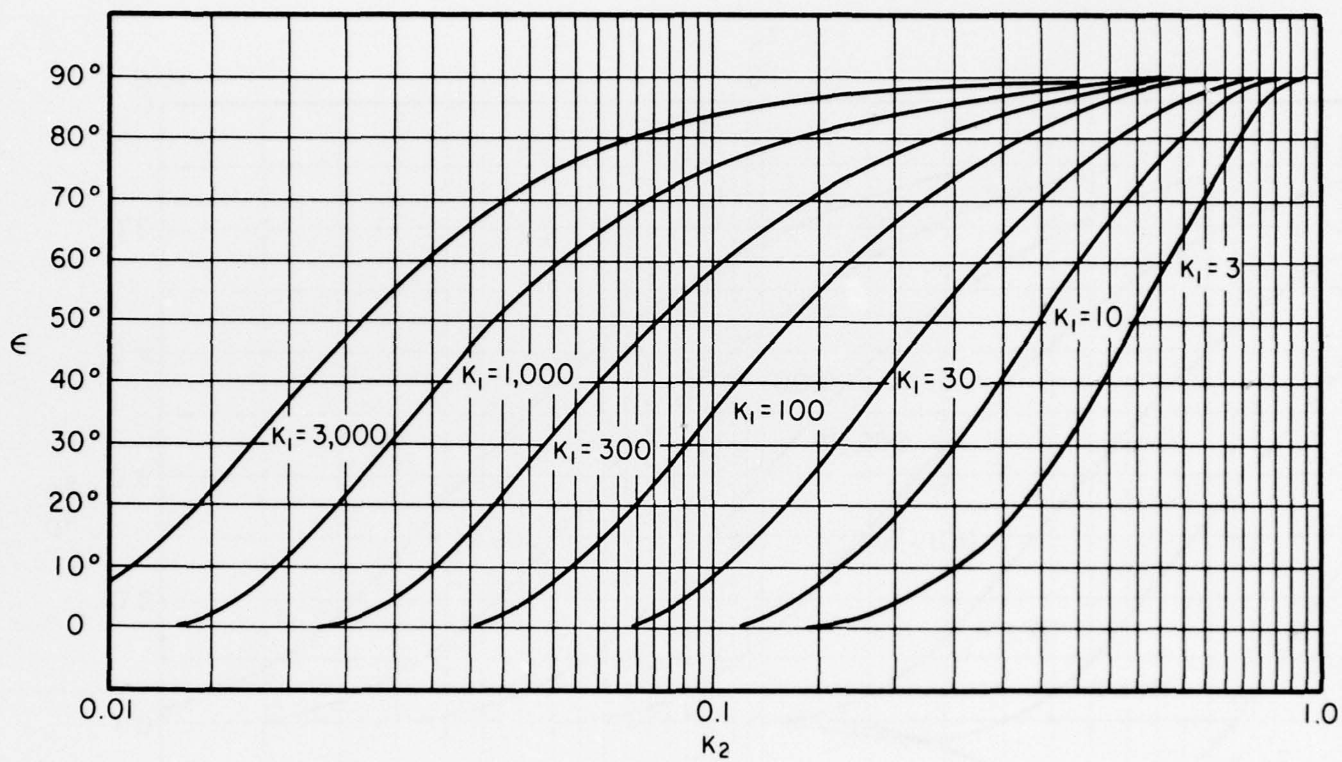

Figure 4. Bay tidal phase lag versus K_1 and K_2.

where L_b is the distance to the farthest point and d_b is the average bay depth.

(c) The inlet channel depth is large compared to the ocean tidal range and the channel depth and width do not vary along the channel. Hydraulic calculations may be made with a reasonable degree of confidence if channel cross-section variations exist but are not too extreme. For irregular jettied or unjettied channels, an effective channel length, L_*, which can be used in place of L, is given by

$$L_* = \sum_{i}^{n} \left(\frac{R}{R_*}\right)\left(\frac{A_c}{A_{c*}}\right)^2 \Delta x \qquad (6)$$

where R and A_c are average values of the channel hydraulic radius and cross-sectional area used in the hydraulic calculations, and R_* and A_{c*} are the hydraulic radius and cross-sectional area at each of n sections of equal length, Δx, spaced along the channel. For jettied inlets the length may be taken as the distance along the channel axis from the seaward end of the jetties to the section on the bayward end of the channel where the flow velocity is diminished to a small percentage (e.g., 20 percent) of the average channel velocity. For unjettied inlets that are not too irregular in cross section, the length may be taken as the distance along the channel axis between the points on each end where the velocity is, for example, 20 percent of the average velocity.

(d) Bay walls are vertical over the bay tidal range. Hydraulic calculations may be made with a reasonable degree of confidence if there is no extensive flooding of tidal flats.

(e) There are negligible density currents at the inlet and negligible inflow to the bay from other sources (rivers, overland flow, precipitation, etc.).

The values for k_{en}, k_{ex}, and f must also be established for calculations to proceed. k_{ex} may be assumed equal to unity ($k_{ex} = 1.0$) and k_{en} will probably vary between approximately 0 and 0.2 as the entrance hydraulic efficiency decreases. A value of $k_{en} = 0.1$ is recommended for most calculations.

The friction factor, f, or Manning's n ($n = 0.093R^{1/6}f^{1/2}$) depends on the bed roughness and flow velocity. For a sandy channel bottom typical of most inlets, f can vary between 0.01 and 0.07 depending on the peak velocity and the phase of the tidal cycle. If no information is

available to estimate the friction factors a value of $f = 0.03$ may be used.

Losses caused by bridge piers, sills, channel bends, etc., must also be accounted for in hydraulic calculations by adding a loss coefficient similar to k_{en} and k_{ex} in the equation defining F. Like k_{en} and k_{ex}, this coefficient defines the number of velocity heads $(V^2/2g)$ lost at a channel disturbance.

IV. INLET CHANNEL STABILITY

Some new inlets formed artificially or as a result of storms will rapidly close while others will remain open for a period of time but undergo variations in cross-sectional area, length, and location (dynamic stability). Inlets "stabilized" by jetties will be more likely to remain open in a fixed position but the channel may erode or shoal in response to environmental conditions. Inlet channel behavior is the result of a complex response to tide and storm-generated flows which attempt to maintain the channel and wave-generated sediment transport to the inlet which attempts to close the channel.

However, several authors have demonstrated that a relationship exists between the tidal prism and inlet throat cross-sectional area for many stable jettied and unjettied inlets located on sandy coasts. Data analyzed by Jarrett (1976)[3] suggest the following relationships for U.S. inlets (Table).

Table. Inlet stability equations.

Location	Jetties	Defining tide	Equation
Atlantic	None or one	Spring	$A_c = 5.37 \times 10^{-6} P^{1.07}$
Gulf	None	Diurnal	$A_c = 3.51 \times 10^{-4} P^{0.86}$
Pacific	None or one	Diurnal	$A_c = 1.91 \times 10^{-6} P^{1.10}$
Atlantic	Two	Spring	$A_c = 5.77 \times 10^{-5} P^{0.95}$
Gulf	Two	Diurnal	$A_c = 3.76 \times 10^{-4} P^{0.86}$
Pacific	Two	Diurnal	$A_c = 5.28 \times 10^{-4} P^{0.85}$

[3]JARRETT, J.T., "Tidal Prism-Inlet Area Relationships," GITI Report 3, U.S. Army, Corps of Engineers, Coastal Engineering Research Center, Fort Belvoir, Va., and U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., Feb. 1976.

In the table, A_c is the minimum cross-sectional area below MSL in square feet and P is the tidal prism in cubic feet for the spring or diurnal tidal range reported in the National Oceanic and Atmospheric Administration, National Ocean Survey Tide Tables (1976)[4].

A solution of the appropriate tidal prism-channel cross-sectional area equation from the table, and the hydraulic characteristic equations using Figures 2, 3, and 4 for the tidal prism and channel area that satisfy both criteria, will yield a predicted stable channel cross-sectional area. It is possible, should the channel be too long or the bay area or tidal range too small, that no common solution to the stability and hydraulic criteria will be found, indicating that no channel cross-sectional area would be stable. Any dredged channel at this location would eventually close if sediment is available to fill the channel.

V. EXAMPLE DESIGN PROBLEM

* * * * * * * * * * * * * * EXAMPLE PROBLEM * * * * * * * * * * * * * *

GIVEN: A bay with a surface area of 2×10^8 square feet (1.86×10^7 square meters) and an average depth of 20 feet (6.1 meters) is located on the Atlantic coast. The tide is semidiurnal (T = 12.4 hours) with a spring range of 4.4 feet (1.34 meters), as given by the National Ocean Survey Tide Tables. An inlet channel, which will be the only entrance to the bay, is to be constructed across the barrier beach which separates the bay from the ocean. The inlet is to provide a navigation passage for small vessels, dilution water to control bay salinity and pollution levels, and a channel for fish migration. The channel is to have a design length of 3,600 feet (1,097 meters) with a pair of vertical sheet pile jetties that will extend the full length of the channel.

FIND:

a. If the channel has a depth below MSL of 12 feet (3.66 meters) and a width of 600 feet (183 meters), what are the maximum flow velocity, bay tidal range and phase lag, and the volume of water flowing into and out of the bay on a tidal cycle (tidal prism) for a tide having the spring range?

b. Evaluate the potential stability of the proposed channel cross section.

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[4]NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, "Tide Tables, East Coast North and South America, Including Greenland," and "Tide Tables, West Coast North and South America, Including the Hawaiian Islands," National Ocean Survey, Rockville, Md., 1976.

SOLUTION:

a. Assume $k_{en} = 0.1$, $k_{ex} = 1.0$, and $f = 0.03$. With $B = 600$ feet and $d = 12$ feet.

$$A_c = BL = 600(12) = 7,200 \text{ square feet (669 square meters)}$$

$$R = \frac{A_c}{(B + 2d)} = \frac{7,200}{(600 + 2(12))} = 11.54 \text{ feet (3.51 meters)}$$

$$F = k_{en} + k_{ex} + \frac{fL}{4R} = 1.0 + 0.1 + \frac{0.03(3,600)}{4(11.54)} = 3.43$$

$$K_1 = \frac{a_s A_b F}{2LA_c} = \frac{(4.4/2)(2)(10^8)\ 3.43}{2(3,600)(7,200)} = 29.1$$

and

$$K_2 = \frac{2\pi}{T} \sqrt{\frac{LA_b}{gA_c}} = \frac{2\pi}{12.4(60)(60)} \sqrt{\frac{3,600(2)\ 10^8}{32.2(7,200)}} \approx 0.25 .$$

From Figures 2, 3, and 4 with the above values of K_1 and K_2

$$V'_m = 0.66$$

$$\frac{a_b}{a_s} = 0.78$$

and

$$\varepsilon = 53°$$

Therefore, from equation (1)

$$V_m = \frac{V'_m 2\pi a_s A_b}{A_c T}$$

$$V_m = \frac{0.66(2)(3.14)(2.2)(2)\ 10^8}{7,200(12.4)(3,600)} = 5.68 \text{ feet (1.73 meters) per second.}$$

Since $a_b/a_s = 0.78$, $a_b = 0.78(2.2) = 1.72$ feet (0.52 meter) and the bay tidal range is 1.72(2) or 3.44 feet (1.05 meters). The tidal prism is $2a_bA_b = 2(1.72)(2)(10^8) = 6.86 \times 10^8$ cubic feet (6.37×10^7 cubic meters) and the bay tidal phase lag is 53° or (53/360) (12.4) = 1.83 hours.

If the average depth of the bay is 20 feet and the distance to the farthest point in the bay is 4 miles, the time, t, it will take for the tide wave to propagate to that point is

$$t = \frac{L_b}{\sqrt{g d_b}} = \frac{4(5,280)}{\sqrt{32.2(20)}} = 832 \text{ seconds or } 0.23 \text{ hour} .$$

Since this time is significantly less than 12.4 hours, the assumption that the bay surface remains horizontal is quite satisfactory.

b. By varying the cross-sectional area of the channel, A_c, assuming that the channel width, B, remains constant and varying the channel depth, d, and recalculating the tidal prism as described above, the effect of channel area on the bay tidal prism can be evaluated and compared with the appropriate equation from the table (Atlantic coast, two jetties, $A_c = 5.77 \times 10^{-5} P^{0.95}$). This is done graphically in Figure 5 which shows a plot of P versus A_c from the hydraulic response calculations and from the stability equation. The common point on the two curves is the solution. It yields a channel cross-sectional area of 19,000 square feet (1,765 square meters) or a depth of 31.7 feet (9.66 meters). This shows that the 600- by 12-foot design channel would be unstable with a strong tendency to erode.

Where the hydraulic response curve lies above the stability curve (as in the example) the tidal prism is too large for the inlet channel area and erosion will likely occur until a stable channel develops. If the hydraulic response curve crosses the stability curve twice, the lower point is an unstable equilibrium point from which the channel can either close or scour to the upper stability point. If the hydraulic response curve is substantially below the stability curve at all points, a stable inlet channel is unlikely to develop and the channel should eventually close.

The stable inlet cross-sectional area depends on other factors (e.g., wave climate, monthly tidal range variations, surface runoff) besides the spring or diurnal tidal prism. As a result, the tidal prism-inlet area equations given in the table only serve as an indication of the approximate stable cross-sectional area. The analysis performed in the example demonstrates that the design channel is very likely to erode to a greater depth; however, that depth, which will fluctuate with time, can vary substantially from the indicated depth of 31.7 feet.

* *

VI. SUMMARY

This report presents simple methods for calculating the maximum channel velocity, bay tidal range, and bay tidal phase lag for a tidal inlet connecting a single bay to the sea. The hydraulic response calculations can then be used to determine the stable channel cross-sectional area for a given channel length, bay geometry, and sea tidal range.

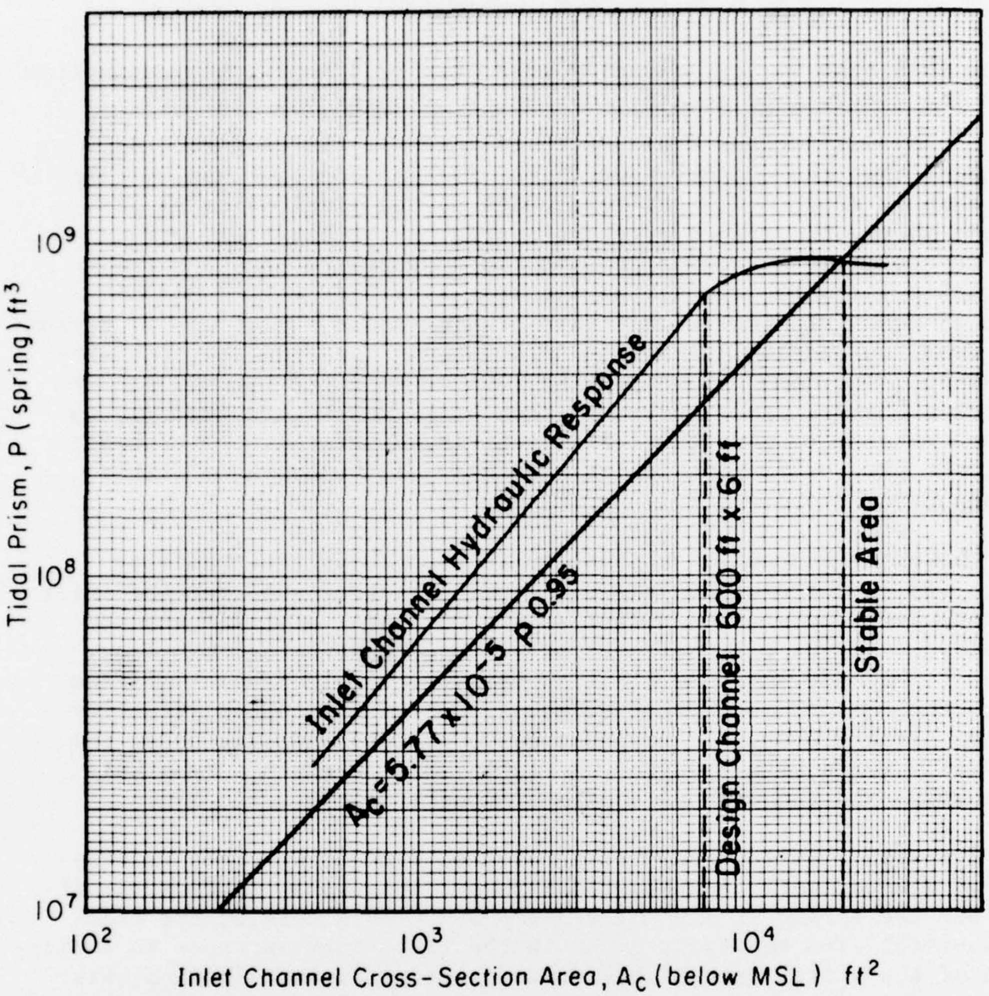

Figure 5. Channel stability analysis.

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Procedures for preliminary analysis of tidal inlet hydraulics and stability / by Robert M. Sorensen. – Fort Belvoir, Va., : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1977.
20 p. : ill. (Coastal engineering technical aid - U.S. Coastal Engineering Research Center ; CETA 77-3)
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